



*Institute of Paper Science and Technology
Atlanta, Georgia*

IPST Technical Paper Series Number 829

Effect of Recycling Fibers on Accelerated Creep

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December 1999

Submitted to
Progress in Paper Recycling

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ABSTRACT

We conducted a study to compare the accelerated creep response in tension of handsheets made from never-dried fibers, once-dried fibers, and combinations of both types. The purpose of the study was to determine if the use of once-dried fibers in linerboard decreases the paper's performance in a cyclic humidity environment. Our "recycled" sheets were made at either the same process conditions or made to have the same tensile strength as the virgin sheets. Equal tensile strength was achieved through additional refining and pressing. Analysis of the results revealed that handsheets made with untreated-once-dried fibers had the highest degree of accelerated creep, but handsheets made from the once-dried-refined fibers yielded results differing little from the sheets made from virgin fibers.

KEYWORDS

Accelerated Creep, Mechanosorptive, Recycled Fibers, Once-dried

INTRODUCTION

It was reported long ago that the mechanical integrity of paper suffers due to changes in the humidity of the surrounding environment (1). Loaded specimens creep more and fail sooner when the relative humidity is cycled rather than maintained at its maximum. This premature failure is one of the main limitations of the performance of corrugated boxes. This curious observation prompted widespread practical and scientific interest. In order to understand the phenomenon, researchers the world over have made measurements on a variety of materials

under numerous conditions. Special terms (“accelerated creep” and the “mechanosorptive effect”) were coined for shorthand reference to the phenomenon. Many explanations were proffered. Nonetheless, accelerated creep is not yet well understood.

Pickett (2) and Selway *et al.* (3) attributed accelerated creep to nonlinear behavior, and we have shown mathematically that material nonlinearity, coupled with transient sorption-induced stress concentrations, exacerbates creep (4). From this viewpoint, creep nonlinearity, hygroexpansivity, moisture sensitivity of mechanical properties, and moisture sorption rate should impact the degree of accelerated creep (4). For this study, the degree of accelerated creep is defined as ratio of the rates of creep with respect to logarithm of time in cyclic humidity and at constant high humidity (4). A higher degree of accelerated creep indicates a faster rate of creep in cyclic humidity as compared to constant humidity. From this perspective, we have investigated the influence of once-dried fibers on accelerated creep.

Recycling influences have been noted in the literature (5-8), but the results are conflicting. Soderberg (5) and Considine *et al.* (6) found little difference in performance in cyclic humidity between recycled and virgin board. On the other hand, Söremark and Fellers (7) and Byrd and Koning (8) found that recycled fibers gave higher accelerated creep than virgin fibers.

EXPERIMENT

We used three furnishes to produce five distinct handsheet types. The pulp types were all derived from the same virgin pulp and consisted of a never-dried pulp, a once-dried pulp, and a once-dried-refined pulp.

Using the three furnishes, the following five Noble and Wood handsheet types were produced:

A: 100% never-dried pulp.

B: 100% once-dried fibers with the same papermaking conditions as sheet A.

- C: the once-dried-refined fibers using conditions to yield a tensile strength equal to that of sheet A.
- D: a blend of 50% virgin and 50% once-dried fibers using the same papermaking conditions as sheet A
- E: a blend of 50% virgin and 50% once-dried-refined fibers using papermaking conditions to give a tensile strength equal to that of sheet A.

The following properties were measured: basis weight, caliper, moisture content, tensile strength, stretch, STFI compressive strength, elastic stiffness, MD/CD stiffness ratio, Gurley porosity, moisture sorption rates between 50 and 90% RH, and hygroexpansivity between 30 and 80% RH.

Tensile creep tests were conducted in the IPST creep tester (4) using 2.5-cm-wide specimens having a gage length of 14 cm. The samples were attached to aluminum tabs with epoxy. One end was held fixed and the other end attached to a dead weight. The sample elongation was measured with an LVDT and recorded as a function of time. In the creep tester, five specimens can be tested at once. The samples are contained in a humidity-controlled chamber.

Several 24-hour creep tests under constant 80% RH and 22°C were conducted for each paper type using two load levels. This allowed for an assessment of the nonlinearity in the creep response. The accelerated creep tests were conducted with the following regime. An initial 4-hour period of constant 80% RH and 22°C followed by ten 2-hour cycles of humidity steps between 30 and 80% RH at 22°C. The cyclic humidity tests were conducted at three load levels.

At least three repetitions of the cyclic creep tests were conducted at each load level. At the highest load level, limited results were obtained because of sample failure during the creep tests.

MATERIALS

Pulp

As received, our never-dried unbleached southern pine kraft pulp had a consistency of 22% and a kappa number of 97. This pulp was washed and beaten in a valley beater to 516 CSF and used as our never-dried pulp. The once-dried pulp was prepared by forming 205 gr/m² handsheets, drying the handsheets close to 0% moisture content, and re-disintegrating the sheets in a British disintegrater. In order to obtain recycled handsheets of equal tensile strength, additional refining with a Valley beater was required. Table 1 provides a summary of the properties of these three pulps.

Table 1. Furnish Properties

Furnish Type	CSF [ml]	Avg. Fiber Length [mm] ¹	WRV	Percent Fines [%] ²
Never-dried	516	2.2	2.5	9.9
Once-dried	600	2.1	1.6	5.5
Once-dried-refined	163	1.6	2.2	9.9
1 weighted-weighted average from Kajaani FS-100 analyzer 2 number 200 mesh in the Britt Jar				

The weighted-weighted fiber average, as defined by TAPPI Standard Test Method T271 om-98, is the ratio of the average of the cube of the fiber length divided by the average of the square of the fiber lengths.

The results given in Table 1 indicate that the once-dried pulp has a higher CSF and lower water retention value (WRV) as compared to the never-dried pulp. The average fiber length for the once-dried pulp is 94% of the virgin length. The once-dried had 45% less fines than the virgin sheet. As expected, the once-dried-refined pulp has significantly reduced CSF, but the percentage of fines is equivalent to the virgin sheet. The extra refining of the once-dried-refined pulp has produced an increase in the WRV so that it is only 12% lower than the never-dried

WRV. Thus, it appears that we have a pulp where we have reversed, at the expense of fiber length and CSF, most of the effects of drying.

Handsheets

After forming and couching, all sheets were dried on a combination nip/press dryer under constant felt restraint of 0.28 MPa (40 psi). The nip pressure in the dryer was set at 490 kN/m (280 pli) for sheets A, B, and D, 1313 kN/m (750 pli) for sheet C, and 656 kN/m (375 pli) for sheet E.

After the handsheets were produced, they were stored at 50% RH. Before testing, the sheets were preconditioned by exposing the sheets to 90% RH for 72 hours followed by 20% RH for 72 hours, and finally placed at 50% RH for at least one week. The temperature at all these conditions was 22°C. This procedure was imposed to stabilize the sheets before testing.

Sheet properties were measured before and after the conditioning stage. This was done to determine if the exposure to high humidity followed by low humidity caused any significant changes. Tables 2 and 3 provide a summary of the physical and mechanical properties of the sheets. Soft platen density was determined as the grammage divided by the soft caliper. The results show that the once-dried sheet had the lowest density, 13% lower than the never-dried sheet. The once-dried-refined sheet had the highest density, 15% higher than the never-dried sheet. The sheets with mixed furnishes had measured densities halfway between the pure furnishes.

Table 2. Summary of Handsheet Properties: Grammage, Caliper, and Density of Sheets

Handsheet Type	Grammage [gr/m ²] (cv*)		Hard Caliper [μm] (cv)		Soft Caliper [μm] (cv)		Soft Platen Density [gr/cm ³] (cv)	
	Before	After	Before	After	Before	After	Before	After
A (never-dried)	213 (0.5)	216 (0.9)	350 (2.8)	352 (2.3)	312 (2.4)	307 (2.2)	0.68 (2.2)	0.71 (2.0)
B (once-dried)	205 (1.5)	203 (5.9)	366 (1.4)	369 (2.3)	330 (2.3)	329 (2.2)	0.62 (1.7)	0.62 (6.4)
C (once-dried-refined)	206 (0.5)	208 (0.6)	298 (0.6)	303 (1.2)	254 (1.4)	253 (1.3)	0.81 (1.2)	0.82 (1.3)
D (50/50 A and B)	210 (0.5)	212 (0.5)	355 (2.1)	357 (1.8)	319 (1.7)	314 (1.5)	0.66 (1.8)	0.67 (1.6)
E (50/50 A and C)	207 (1.0)	209 (1.1)	326 (1.6)	326 (1.5)	287 (1.5)	291 (1.7)	0.72 (1.4)	0.72 (1.5)
* cv is the coefficient of variation (%) for the mean values given in the table								

The specific stiffnesses, given in Table 3, show that the never-dried (A) and the once-dried-refined (C) sheets had approximately the same specific stiffnesses, whereas the in-plane stiffness of the once-dried sheet (B) was about 21% lower than that of the never-dried sheet. The preconditioning cycle produced a 2 to 5% drop in the in-plane specific stiffnesses for all of the sheet types.

Table 3 documents that the extensional stiffness, strength, and STFI compression strength of the never-dried (A) and once-dried-refined (C) sheets were similar. The once-dried sheet (B) had a 22% lower stiffness, 42% lower strength, and 36% lower STFI than the never-dried handsheet (A). The stretch of the once-dried sheet (B) was 30% lower than the stretch of the never-dried sheet (A). The exposure to high moisture content caused approximately a 15% decrease in the extensional stiffness.

Table 3. Summary of Handsheet Properties: Mechanical Properties

Sheet Type	Ultrasonic Stiffness [km ² /sec ²] (cv*)		Extensional Stiffness [N/mm] (cv*)		Strength [N/mm] (cv)		Stretch [%] (cv)		STFI [N/mm] (cv)		Gurley Porosity [sec] (cv)	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
A	9.41 (2.5)	9.04 (2.9)	1150 (3.9)	985 (4.8)	11.2 (7.5)	10.3 (3.2)	2.5 (10.9)	2.7 (5.0)	6.35 (0.9)	6.07 (4.3)	14.5 (8.6)	16.8 (8.5)
B	7.43 (1.8)	7.14 (2.8)	880 (11.5)	768 (15.2)	6.0 (10.9)	6.0 (7.4)	1.4 (9.6)	1.9 (6.9)	4.11 (2.7)	3.86 (2.0)	4.9 (6.1)	4.2 (7.3)
C	9.67 (1.7)	9.24 (2.6)	1200 (3.9)	1030 (4.0)	10.7 (6.0)	10.3 (5.2)	2.2 (10.3)	2.8 (7.7)	6.51 (3.0)	5.96 (0.6)	220.8 (4.8)	170.2 (2.5)
D	8.58 (2.5)	8.20 (3.7)	1033 (4.1)	952 (9.2)	8.6 (3.1)	8.7 (9.8)	2.0 (9.1)	2.4 (8.9)	5.71 (10.5)	5.11 (4.6)	8.0 (10.1)	8.5 (5.5)
E	9.45 (2.0)	9.09 (4.4)	1150 (4.0)	1010 (7.8)	10.9 (3.5)	9.5 (8.7)	2.4 (11.0)	2.4 (14.1)	6.52 (0.9)	5.82 (1.5)	51.5 (6.5)	52.1 (4.4)
* cv is the coefficient of variation (%) for the mean values given in the table												

The hygroexpansivity of the sheets was measured using the creep tester with a low applied load of 80 grams. Table 4 provides the hygroexpansive strain resulting from a change in relative humidity from 30 to 80% RH. Each value is the average of three cycles of humidity; the coefficient of variation for a single sample was less than 0.1%. The once-dried handsheet (B) had the lowest hygroexpansion, and the once-dried-refined handsheet (C) had the largest hygroexpansion.

Table 4. Summary of Handsheet Properties: Hygroexpansivity

Handsheet Type	Hygroexpansive Strain [%] from 30 to 80 % RH	
	Test 1	Test 2
A (never-dried)	0.41	0.42
B (once-dried)	0.33	0.34
C (once-dried-refined)	0.48	0.45
D (50/50 A and B)	0.38	0.39
E (50/50 A and C)	0.46	0.47

Figure 1 shows moisture sorption data, acquired from gravimetric measurements, for the five handsheet types from 50% to 90% RH. Notice that all of the sheets had very similar moisture sorption curves and that the total sheet weight increased about 7% for all sheets.

The nonlinearity of the creep strain was assessed by the extent to which the above ratio exceeded unity. Larger values indicate that the higher load created more creep strain compared to the lower load. Table 5 shows that the once-dried sheet (B) had a higher degree of nonlinearity at earlier times than both the never-dried (A) and the never-dried-refined sheets (C). At 24 hours, the degree of nonlinearity was the same for all the sheets. The second set of columns in Table 5 shows the ratios normalized to the never-dried board.

Handsheet Type	Ratio of creep strain per unit load for 65.4 N and 38.3 N load			Normalized ratio of creep strain load for 65.4 N and 38.3 N load		
	0.083 hours	0.25 hours	24 hours	0.083 hours	0.25 hours	24 hours
A (never-dried)	1.82	1.75	1.32	1	1	1
B (once-dried)	2.22	1.97	1.31	1.22	1.12	0.99
C (once-dried-refined)	1.93	1.86	1.38	1.06	1.06	1.05

[strain1/load1]/[strain2/load2] ; load1=65.4 N, load2=38.3 N, strain is creep strain at a given time.

CYCLIC CREEP RESULTS

The cyclic creep tests were conducted in the IPST creep tester, which allows five samples to be tested at once. For an experimental run, one specimen of each handsheet type was tested. Testing began by loading the sample with the dead load while raising the humidity in the chamber to 80% RH and 22°C. After 4 hours, the humidity cycling began. Two hour cycles were used, one hour at 30% RH and one hour at 80% RH. During the entire test, the time, displacement, RH, and temperature were recorded every 15 sec. The degree of accelerated creep was determined, and results are shown in Figure 2. At the highest load level, results were not obtained for sheet type B because all samples broke.

The degree of accelerated creep was essentially the same for all the handsheet types except the once-dried sheets. The once-dried sheets (B) had an accelerated creep that was about 25% higher than the other sheets. At the lowest load, we found that the once-dried sheet (B) gave a large scatter of results and a much lower average degree of accelerated creep. Thus, we conducted one test at the low load level for all the samples. The degree of accelerated creep was lower for all these samples.

The results reveal that the mixed furnishes (D and E) did not exhibit increased accelerated creep compared to the pure furnishes (A, B, and C). This shows that heterogeneity caused by mixing once-dried and never-dried fibers does not cause a significant increase in accelerated creep, and it implies that heterogeneity of this type is not influencing the accelerated creep.

Because the once-dried sheet (B) is weaker and creeps faster at a given load level than the other sheets, we felt it was reasonable to compare the degree of accelerated creep as a function of creep load expressed as a percentage of the sheet's tensile strength. This is shown in Figure 3. From this viewpoint, we see that the degree of accelerated creep of the once-dried sheet (B) is only slightly higher than that of the other sheets. The other four sheet types show very little

difference in response. A t-test for the results at the 25% strength level produced a 77% probability that the mean degree of accelerated creep is different for the never-dried (A) and once-dried sheets (B). Thus, we can conclude that the differences in degree of accelerated creep for the handsheets are not large when compared at the same percentage of tensile strength.

Figure 4 shows the six repetitions of the cyclic-humidity creep curve for both the never-dried (A) and once-dried sheets (B) loaded to the same dead weight (65.4 N). In the figure, the zero strain point was taken at the time where the humidity cycles began. This makes it easy to visualize the repeatability of the tests and compare two tests together. It is clear from the figure that the once-dried paperboard crept faster than the never-dried paperboard. The once-dried sheet also had more scatter in the data. The calculations show that the degree of accelerated creep was also higher for the once-dried paperboard. Note that two of the recycled samples failed during the cycling.

Figure 5 shows the comparison for the never-dried (A) and the once-dried-refined (C) paperboards loaded to the same dead weight (65.4 N). It is clear from the curves in this figure that there was very little difference in the response of these two sheet types.

CORRELATION TO MECHANICAL PROPERTIES

We found that the degree of accelerated creep was slightly higher for the once-dried sheets (B) as compared to the other four sheet types (A, C, D, and E). When compared on an equal strength basis, the difference was even smaller. Table 6 provides the results of a least squares fit between measured properties and the degree of accelerated creep for the five sheet types. The degree of accelerated creep for the 65.4 N load case was used in the linear regression. The values of degree of accelerated creep and the measured properties were normalized to vary between zero and one. Thus, a perfect linear fit of the data would yield both the slope and the R^2 value equal to one.

Table 6. Correlation between degree of accelerated creep and measured properties

	Extensional Stiffness	STFI	Ultrasonic stiffness	Strength	Nonlinearity of creep
Normalized slope	-0.94	-0.88	-0.97	-0.87	+0.89
R ²	0.90	0.86	0.83	0.83	0.74

	Stretch	Hygro-expansivity	Soft density	Gurley Porosity
Normalized slope	-0.86	-0.76	-0.65	-0.27
R ²	0.63	0.60	0.37	0.084

The results in the table show that the extensional stiffness, STFI, ultrasonic stiffness, and tensile strength all show fairly good correlation to the degree of accelerated creep. As the stiffness and strength of the sheet increase, the degree of accelerated creep decreases. For this study, one could conjecture that the same sheet characteristics that lead to high stiffness and strength also lead to decreased accelerated creep. It is well known that stiffness and strength increase as the relative bonded area increases, the intrinsic bond strength increases, and the fiber stiffness and strength increase.

The proposed mechanism for accelerated creep (4) predicts that increased nonlinearity in the creep properties will cause higher degrees of accelerated creep. The data in Table 6 is consistent with this prediction. The two quantities are positively correlated with an R² of 0.74.

The model (4) also suggests that the degree of accelerated creep should increase as the hygroexpansivity increases. Our results do not conform to this hypothesis. In fact, the data show a trend that the degree of accelerated creep was lower for the sheets with higher hygroexpansivity, although the fit for this data is not good, R²=0.60. This negative result indicates that the differences in hygroexpansivities were not great enough to overcome other differences such as the nonlinear creep behavior of the sheets.

The stretch, density, and Gurley porosity did not correlate well with the degree of accelerated creep. One may have expected that porosity of the sheet would have an effect because it may

influence the sorption rate of moisture into the sheet. This is not the case, since the porosity values of the sheets are quite different, but the moisture sorption behavior was very similar for the five sheet types.

CONCLUSIONS

Based on our results, we conclude that paper made from untreated once-dried fibers yields a sheet with a higher degree of accelerated creep than never-dried sheets, but, by refining the fibers, one can eliminate the excess accelerated creep. Sheets made from once-dried-refined fibers, produced in a manner to give equal tensile strength to the never-dried sheets, had the same degree of accelerated creep as the never-dried sheets. In our study, the equal accelerated creep performance was achieved at the expense of lower freeness and higher density.

With a mixture of 50% never-dried fibers and 50% once-dried fibers, we did not observe adverse effects of the once-dried fibers. Since we know that the case of 100% once-dried fibers lead to a higher degree of accelerated creep, we hypothesize that as the percentage of once-dried untreated fibers increases towards 100%, one would see an increase in the degree of accelerated creep.

When we compared the degree of accelerated creep for the various sheet types loaded to the same percentage of their tensile strength, we found that the difference between the never-dried and once-dried sheets was smaller. We hypothesize that the physical attributes that cause the once-dried sheet to have a lower tensile strength also leads to increased accelerated creep. This could be tied to a lower degree of bonding in the sheet, less fines, or different fiber properties. The idea of nonlinear creep properties as a contributor to accelerated creep appears to be borne out in this study, since sheets made from once-dried fibers showed the highest degree of accelerated creep and the highest nonlinearity in creep, but the lowest hygroexpansion.

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Acknowledgments: We are grateful for the direct financial support of this project from both the Containerboard Group Technical Division of AF&PA and IPST. We recognize and appreciate the contributions to this project from Mrs. Kennisha Collins, Mrs. Miranda Bliss, and Mr. Andy Brown.

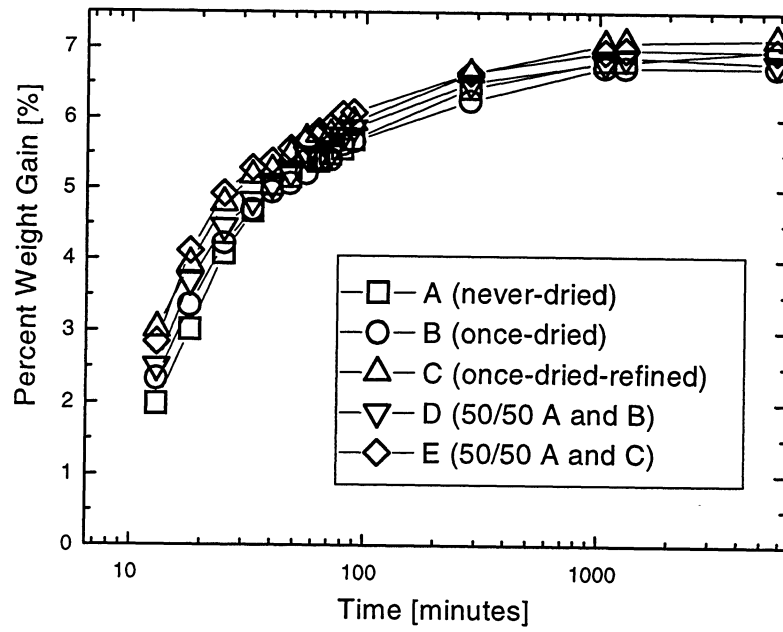


Figure 1. Percent moisture gain from 50 to 90% RH.

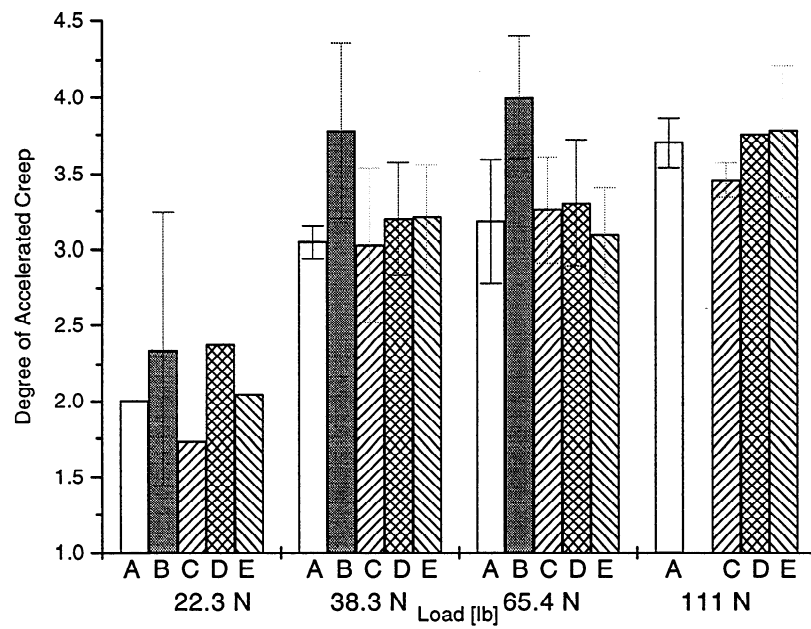


Figure 2. Degree of accelerated creep for the five types of handsheets (A =never-dried, B=once-dried, C=once-dried-refined, D=50/50 A and B, and E =50/50 A and C).

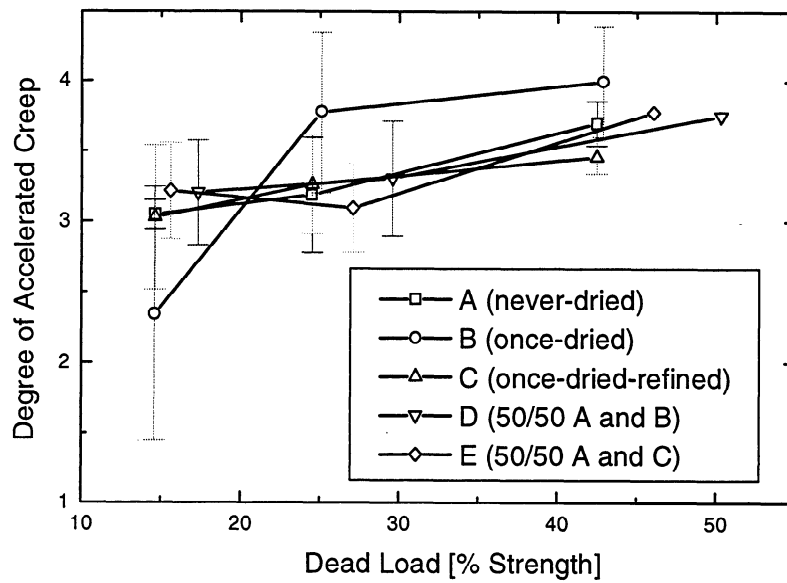
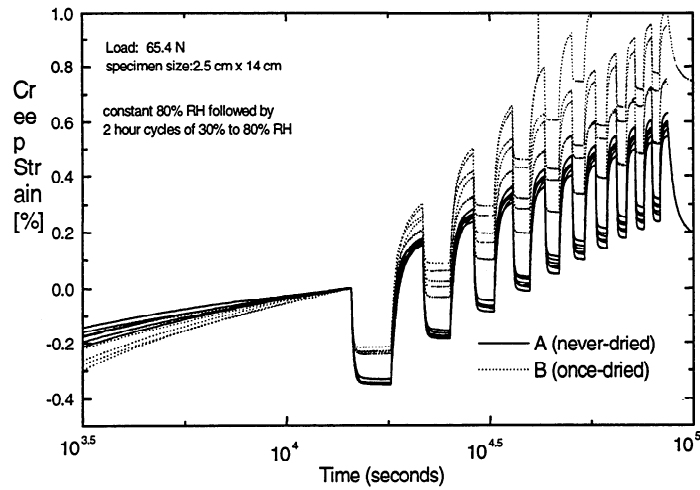
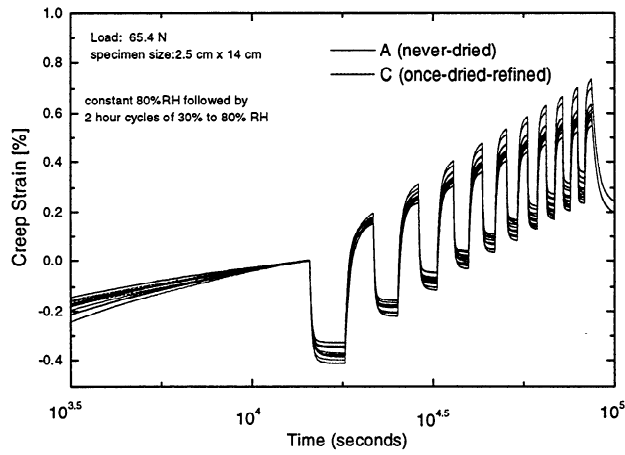


Figure 3. Degree of accelerated creep as a function of load expressed as percent of tensile strength. (A =never-dried, B=once-dried, C=once-dried-refined, D=50/50 A and B, and E =50/50 A and C).



For the purpose of comparison, zero strain is assigned to the time where the humidity cycles begin.

Figure 4. Comparison of cyclic-humidity creep curves for sheets made from never-dried fiber (A) and once-dried fiber (B).



For the purpose of comparison zero strain is assigned to the time where the humidity cycles begin.

Figure 5. Comparison of cyclic-humidity creep curves for sheets made from never-dried fiber (A) and once-dried fiber (B).

